Entered

DEVELOPMENT OF FUNCTIONAL RELATIONSHIP AND TOOL REPLACEMENT CRITERIA IN ULTRASONIC MACHINING

By

ANIL KUMAR KAPOOR

DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR

SEPTEMBER, 1973

[redacted]

DEVELOPMENT OF FUNCTIONAL RELATIONSHIP AND TOOL REPLACEMENT CRITERIA IN ULTRASONIC MACHINING

A Thesis Submitted
In Partial Fulfilment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY

By

ANIL KUMAR KAPOOR

to the

DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR

SEPTEMBER, 1973

1.9.73

CERTIFICATE

This is to certify that the work "Development of functional relationship and tool replacement criteria in ultrasonic machining" by Anil Kumar Kapoor has been carried out under my supervision and has not been submitted elsewhere for a degree.

1.9.73

(Dr. G.S.KAINTH)
Assistant Professor
Department of Mechanical Engineering
I.I.T. Kanpur

ACKNOWLEDGEMENTS

I am deeply indebted to Dr. G. S. Kainth for his invaluable guidance and constant inspiration in course of this work.

Thanks are due to Mr. O.P. Bajaj for his help in conducting the experiments on the ultrasonic machine. I am also grateful to Mr. S.D. Kothari and Mr. S.C.Rastogi for their cooperation in completion of this work. Lastly I would like to thank Mr. D.P. Saini for his skilful typing of the manuscript.

A.K.Kapoor

[redacted]

TABLE OF CONTENTS

LIST OF FIGURES

[redacted]

NOTATIONS

ADC	:	Actual Depth Cut
AMR	:	Average Machining Rate
C	:	Concentrations
L	:	Load
MR	:	Machining Rate
t	:	Time
TWR	:	Tool Wear Rate
VDC	:	Virtual Depth Cut
VMR	:	Virtual Machining Rate

[redacted]

DEVELOPMENT OF FUNCTIONAL RELATIONSHIP
AND
TOOL REPLACEMENT CRITERIA
IN
ULTRASONIC MACHINING

A Thesis Submitted
In Partial Fulfilment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY
by
Anil Kumar Kapoor

to the
DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY, KANPUR
SEPTEMBER 1973

SYNOPSIS

Material removal rate and tool wear in ultrasonic machining depends on many factors such as amplitude and frequency of vibration of tool, static load, concentration and material of workpiece. Experiments are conducted on soda glass using mild steel tool with load varying from 0.476 Kg. to 0.93 Kg. and slurry concentration (by volume) varying from 0.125 to 0.25. Emery of 120 mesh is used as abrasive. In present work, functional relationship of machining rate with load, concentration and time has been established taking other parameters constant. Functional relationship of tool wear rate with static load has also been established.

[redacted]

Machining rate relationship, thus obtained, is used to find the optimal time after which the tool should be replaced. The optimal tool replacement is based on

(i) the minimum cost criterion

(ii) the maximum production rate criterion.

[redacted]

CHAPTER I

INTRODUCTION AND LITERATURE SURVEY

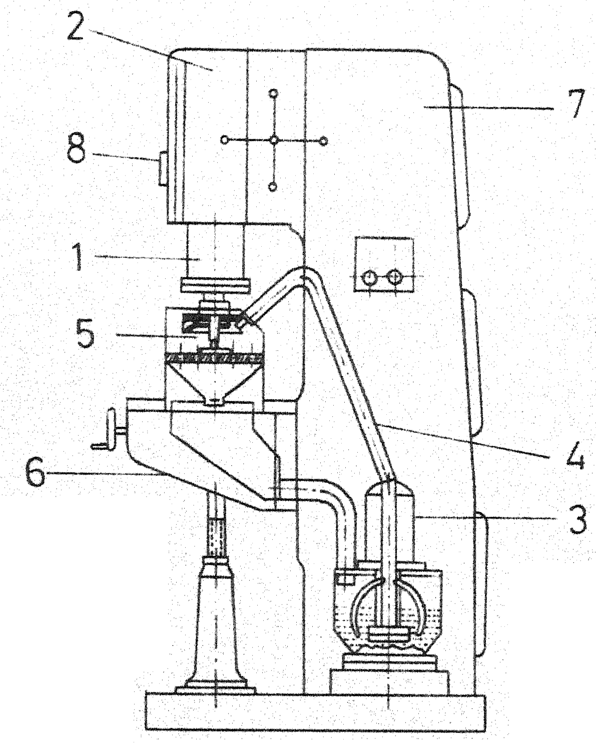
1.1 INTRODUCTION

Current techniques for mechanical working of materials are highly developed. Machine tools have been greatly improved in recent years to solve many of the varied and complex problems arising out of rapid advances in technology.

However, hard and brittle materials such as germanium, silcon, ferrites, ceramics, glass, quartz are difficult to machine because these materials often can not withstand high forces encountered in conventional machining processes. The need for machining these materials has led to the introduction of ultrasonic machining.

In ultrasonic machining, the material is removed by a tool vibrating with small amplitude of the order of 0.001" while abrasive slurry is supplied between the tool and the workpiece. The material is removed in the form of small particles. The total rate of removal is sufficient for practical purposes as there are large number of particles under the tool vibrating at frequencies of about 20-25 KCS. Thus

[redacted]



1. ACOUSTIC HEAD
2. FEED MECHANISM
3. ABRASIVE FEED PUMP
4. PIPES
5. JETS
6. TABLE
7. FRAME
8. POSITION INDICATOR

Set-up of ultrasonic mechine

FIG.1

tool produces a cavity whose profile corresponds to that of the tool. Combinations of movements of the tool allow one to perform a variety of operations analogous to those of ordinary milling, shaping, profile milling on brittle materials. The abrasive also causes wear of the tool.

Current machines (Fig.1) have several specific features such as, an acoustic head, feed mechanism, abrasive feed system (including, pump, pipes and jet), and power source (not shown). In addition, there are features found in ordinary machine tools such as the table, frame and position indicator. The acoustic head contains the electromechanical converter, which drives the tool via a special holder (waveguide). The feed mechanism applies the necessary static force between tool and workpiece. The abrasive feed system continuously brings in fresh abrasive to the cutting area, removes metal particles and cools the tool and workpiece.

1.2 LITERATURE SURVEY

Miller (1) was the first to study the rate of cutting in ultrasonic machining. He assumed that the particles are embedded in the workpiece and tool by the applied force causing plastic deformation and work hardening of the material. The hardened portions are removed by chipping action.

[redacted]

This theory seems to be unjustified, because it assumes dependence of rate of material removal on work hardening which implies that the work material is plastic. However, most materials that are machined by ultrasonic machining are brittle.

Shaw (2) attributed the material removal, mainly, to two mechanisms, viz,

1. direct impact of the tool on grains in contact with the workpiece and
2. the impact of grains accelerated by the tool.

He gave an expression of depth of indentation as below

$$h = \left[\frac{8F_s y_o d}{\pi kHC(1+q)} \right]^{1/2}$$

where F_s static force

y_o amplitude of vibration of tool

q Ratio of hardness of the workpiece to that of the tool

C concentration of the abrasive slurry

k constant of proportionality.

This theory is based on a correct conception of the process as has been confirmed by subsequent experiments by Rozenberg (5) using high speed cinematography. However,

Shaw's theory does not agree with the experimental results regarding the effects of frequency, amplitude and force on material removal rate. Shaw assumed that all the particles are spherical in shape and take part in machining. In fact, the particles are irregular and only those large particles, which stand out above the small ones, take part in the material removal. The crushing of grains at high loads causes a fall in the rate of material removal. This effect is not taken into account in this theory.

Dikushin and Barke (3) related the energy consumed in removing the material from the workpiece to the amplitude and force of vibration using the laws of conservation of energy and momentum. They considered the vibration of the mass of the concentrator, from the end of the tool to the first displacement node of the concentrator assuming sinosoidal motion of the tool up to the time of contact. This theory did not predict quantitatively the material removal rate.

Kazantsev (4) took into account the non-uniformily in the grain size. He assumed that there are only some active grains with which the tool makes contact. Taking a linear relationship between the fraction of active grits and the ratio ($\delta/2R$) (where δ is the grain depth of indentation and R, the radius of grains taken as spheres), he derived an expression for the material removal rate. But his theoretical

[redacted]

results did not compare favourably with the experimental work done by others (5).

Rozenberg (5) gave a qualitative analysis of the nature of the damage in ultrasonic cutting. He assumed that the volume of damaged material is dependent on the maximal stress and the grain size. This means that the inhomogeneity in the grain size has a marked effect on the damage.

Kaczmarek, Kops and Shaw (6) deal with economics of ultrasonic machining. The considered the importance of the behaviour of the individual grains in the process, as the abrasive grains in the slurry constitute the actual machining elements. For a given charge of abras ive, the mean particle size is reduced with working time and the initially sharp edges become dull. This causes a decrease in the rate of material removal with time.

The longer the time between abrasive charges, the smaller will be the abrasive cost per unit volume removed. On the other hand, the cost of machine operator and overhead will increase as the rate of removal is decreased due to disintegration of abrasive particles. Considering these factors, they (6) proposed an expression for optimum abrasive replacement time.

W. Pentland and J.A. Kktermanis (7) gave some feasibility studies for improving ultrasonic machining rates.

They reported on the factors influencing material removal rate by considering the effects of cavitation, low temp, embrittlement of the work material, amplitude of tool vibration, grit size, method of application of slurry and heat treatment of the workpiece. Tool penetration rates were invariably highest for the annealed conditions, with lower rates for normalized and still lower rates for the oil quenched specimens. The finding is contrary to generally accepted practice for this process. Increases in removal rates of the order of 10 to 70% were obtained with 50°C increase in temperature of slurry using 240 and 400 grit abrasive slurries.

H.W. Baker (8) gave information about tool wear rates for different combinations of tool and workpiece material operating on glass, using a boron carbide abrasive the ratio of tool wear to stock removal is about 0.1% for tools made of tungsten carbide and about 1% for mild steel stools. When cutting lungsten carbide itself these figures are increased to 110 percent and 88 percent (8). He compared cutting speeds in various brittle materials , industrial ceramics and metals using boron carbide, silicon carbide and alumina as abrasives respectively. Machining rates were highest for baron carbide. He also compared machining rates for different grit sizes. Higher abrasive sizes gave higher machining rates.

[redacted]

J.R. Fredrick (9) compared cutting rates for different tool shapes. For glass as work material, and mild steel as tool material, he showed that machining rates were higher for a triangular base tool as compared to a circular tool. Also tool wear rates were less in a triangular base tool.

Literature survey shows that material removal rate depends on many factors such as amplitude and frequency of vibration of tool, static load, concentration and type and size of abrasive particles (4,5,6,8). Present work establishes functional relationship of machining rate with static load, concentration and time taking other factors constant.

Tool wear also depends upon above-mentioned factors (4,5,6,8). Normal practice is to give wear rate as a percentage of machining rate (8,9). A functional relationship of tool wear rate with static load, and concentration is established.

Machining rate relation thus obtained is used to find the optimal time after which tool should be replaced.

[redacted]

CHAPTER-II

TOOL REPLACEMENT CRITERIA IN ULTRASONIC MACHINING

2.1 INTRODUCTION

The tool is generally made from a tough material so that it does not chip easily. However, as a result of contact with the abrasive and cavitation effect, the tool also wears out appreciably. Most of the wear occurs at the end of the tool. However, the side wear is also significant, (about 10% of the end wear)(5) and affects the accuracy of the job. The longitudinal wear obtained in tools is found to be least for tough steels and greatest for brittle materials (8). The wear is not large if the workpiece is of glass, semiconductor, but it is very high for tungsten carbides. It is usual to specify the wear as a percentage of machining rate. With mild steel as tool material, wear rate as percentage of machining rate are

(i) 0.5 to 3 percent for germanium, silicon, ferrites, optical glass, soda glass and quartz

(ii) 12 percent for corundum

(iii) 50 percent for ruby

(iv) 70 percent for tungsten carbide, and

[redacted]

(v) 100 percent for hardened steel.

Side wear of tool introduces an additional effect of increasing the angle of the hole and rounding the sharp corners.

In ultrasonic machining, a resonant tool is designed in order to obtain sufficient amplitude at the tool tip. This is achieved by having a tool of length equal to half-wavelength or its multiple (5). It is known that as operation is continued the machining rate decreases with time (5,6). The factors that account for the decrease in machining rate with time are (5,6)

(a) likely reduction in size of abrasive particles due to crushing of grains (6)

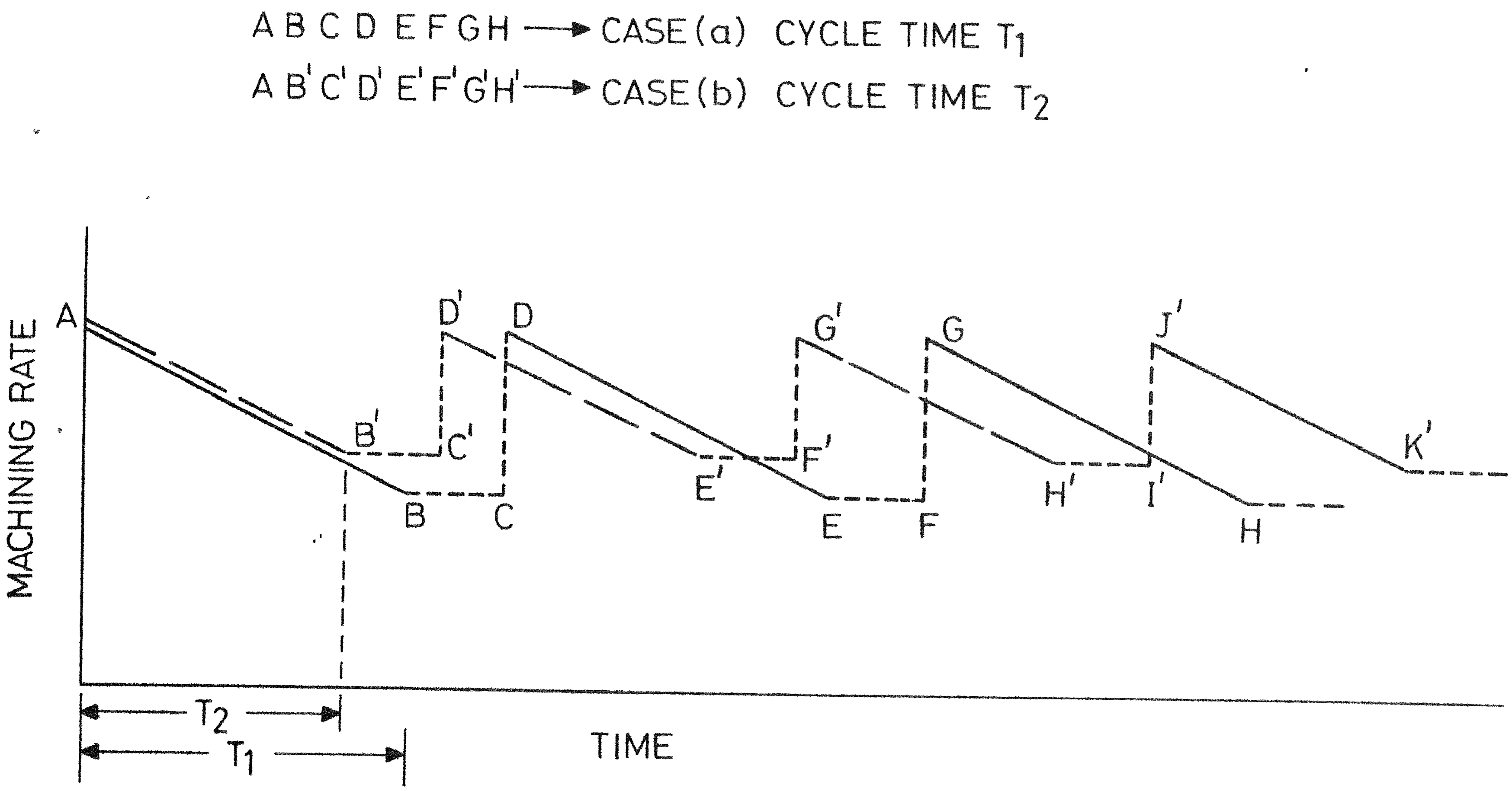
(b) likely reduction in amplitude of vibration due to shortening of length of the tool caused by tool wear, and

(c) departure of system from resonance conditions.

Thus with decreased machining rate, for a given job whole operation is going to take more time. In practice the tool is replaced when the side tool wear becomes excessive giving rise to unacceptable tapered holes. However, it is desirable to replace the tool before the machining rate falls to an uneconomical value. Economical tool replacement policy may be based on

(i) minimum cost criterion

(ii) maximum production rate criterion.



Tool replacement model

FIG. 2

2.2 MODEL FOR TOOL REPLACEMENT

Tool replacement model is shown in Fig. 2. It is assumed that operation starts with a new tool and corresponding machining rate is at A. In case (a), after a cycle time of T_1, machining rate comes down to a value equal to B and it is decided to change the tool. B C represents tool replacement time. At D new tool comes into operation and same cycle is repeated. In case (b), after a cycle time of T_2, machining rate comes down to a value equal to B', when it is decided to change the tool. $B'C'$ represents tool replacement time. At D' new tool starts machining and same cycle is repeated. In the two cases discussed above total cost incurred is different, because of difference in cycle times. Present criteria develops a model to find out a value of T , after which tool should be replaced so that

(i) total cost incurred is minimum or

(ii) production rate is maximum.

Let

T be the time after which tool is to be replaced

N be the total number of jobs to be made

V be the volume removed in machining a hole in the job.

Total volume to be removed = N.V

Let machining rate be a function of time so that MR = $\phi(t)$

[redacted]

Volume removed per tool replacement cycle = $\int_0^T \phi(t)dt.A$

where A is the area of hole

$$\text{Number of cycles} = \left\lfloor \frac{N.\ V}{\int_0^T \phi(t)dt.A} + 1 \right\rfloor$$

$$= \lfloor n_r + 1 \rfloor$$

$$\text{where } n_r = \frac{N.V}{\int_0^T \phi(t)dt.A}$$

Here the symbol $\lfloor x \rfloor$ represents lower integar of x.

Number of tools = $\lfloor n_r + 1 \rfloor$

Total time of operation = $n_r.T$

Tool replacement criteria may be based on

(i) Minimum cost criterion

(ii) Maximum production rate criterion

(i) <u>Minimum Cost Criterion</u>

It is known that the wear of tool is one of the causes of decrease in machining rate with time. If one continues to operate with a worn out tool, the whole operation will take a longer time. However, if it is decided to replace the tool, the costs of the new tool and tool replacement will be incurred. Minimum cost criterion provides an optimal balance of these costs.

[redacted]

Let

C_o be the cost of labour per unit time

C_e be the cost of a tool

t_{ch} be the time taken in replacing a tool

Then total cost C = cost of operation of machine + cost of tools + cost of tool replacement.

$$C = n_r * T * C_o + [n_r + 1] * C_e + [n_r + 1] * C_o * t_{ch} \qquad (2.2.1)$$

To get a value of T, minimising the total cost, the above function is differentiated with respect to T and equated to zero.

(ii) Maximum Production Rate Criterion

Time to machine one job will be equal to the time needed for actual machining plus the tool replacement time per job

$$\text{Time to machine one job} = \frac{n_r . T}{N} + \frac{[n_r + 1] V}{N} . t_{ch}$$

$$\text{Therefore, the production rate } Z = \frac{1}{\frac{n_r . T}{N} + \frac{[n_r + 1]\, t_{ch}}{N}} \qquad (2.2.2)$$

To maximise function Z, it is differentiated with respect to T and equated to zero.

[redacted]

CHAPTER-III

EXPERIMENTAL INVESTIGATION

Experiments have been conducted

(a) to develop a functional relationship of machining rate with load, concentration and time

(b) to develop tool replacement criteria.

The experiments are conducted on 200 watt Cavitron Drilling Machine. The ultrasonic transducer is driven by an oscillator and power amplifier at a resonating frequency of 25.5 KC. and an amplitude of 0.001". Soda glass is machined by using 1/2" dia tool made of mild steel. Emery (abrasive) of 120 mesh is used with water to form slurry for machining. Demineralised water is used for cooling purposes and for making slurry. Machining rates are found by noting the depths of tool penetration from a position indicator on the machine. Virtual depth cut is given by the tool penetration whereas actual depth cut (that is actual depth of hole drilled) is measured by a depth gauge.

Tool wear is measured by a microscope attached to the machine. Microscope is focussed on the tool before starting the operation and reading on the scale is noted.

[redacted]

After machining, the tool is brought back to the static position and reading of the scale on the microscope is noted again. Difference of the two readings gives tool wear during the time of operation.

Experiments are carried out at static loads of 0.476 Kg, 0.703 Kg, 0.812 Kg, 0.93 Kg. and concentrations of 0.125, 0.143, 0.167, 0.2 and 0.25. Concentration is taken as ratio of the volume of abrasive to the volumeof slurry with water. Each set of experiments is conducted by keeping the concentration constant and varying the load. The used slurry is removed from the system and fresh slurry is used for each load. The tests are done in increasing order of concentration to avoid the contamination of the slurry from any abrasive particles remaining in the system from the previous set.

[redacted]

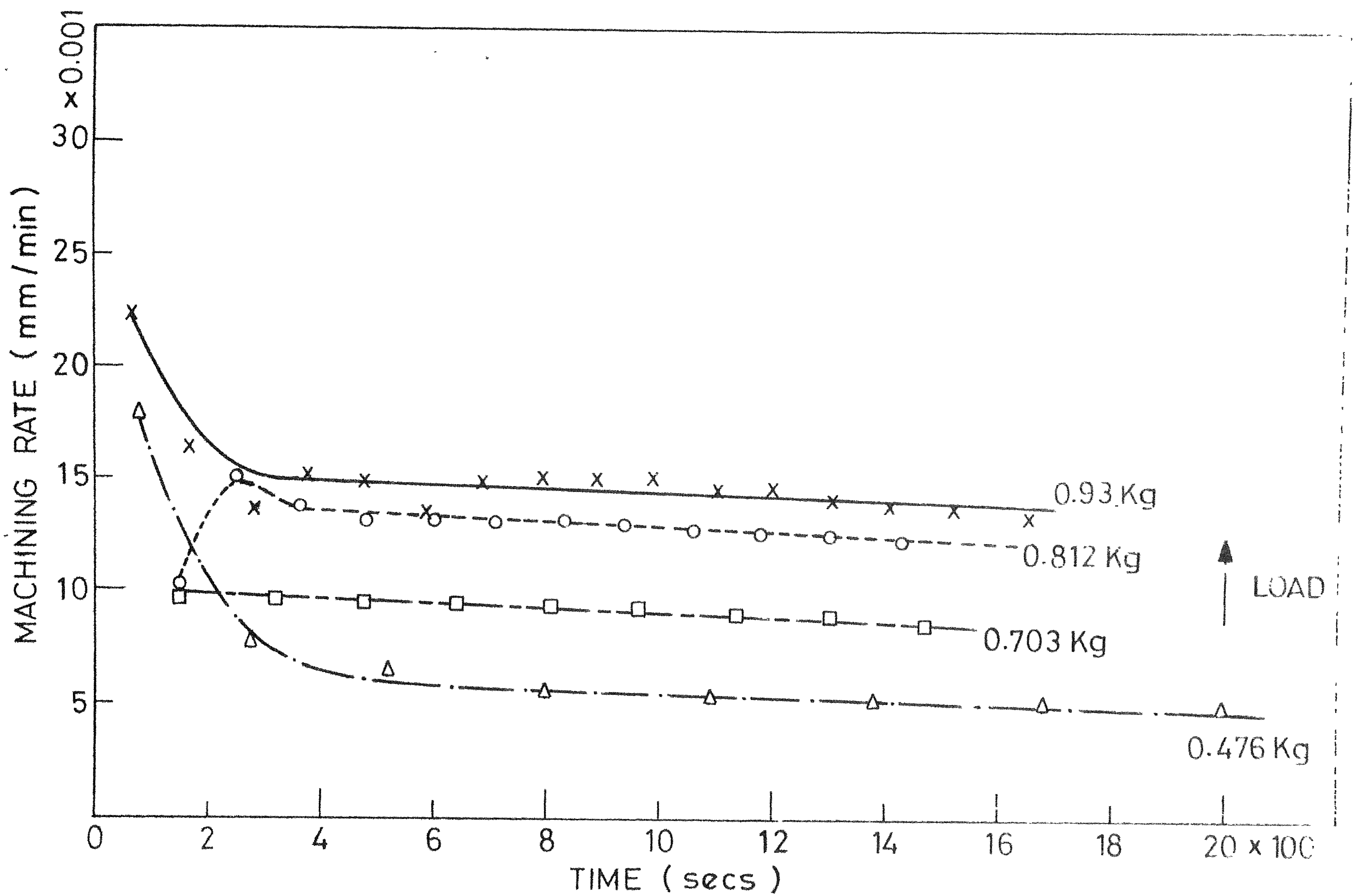
CHAPTER-IV

RESULTS AND DISCUSSIONS

4.1 VARIATION OF MACHINING RATE WITH LOAD, CONCENTRATION AND TIME

Figures 3 to 7 show variation of machining rate with time under different combinations of loads and concentrations. It is clear that in all the cases, system is in transitional state initially. In general, the machining rates decrease rapidly with time in the initial stages. However, in all the cases the variation of machining rate with time becomes linear after a maximum stablising time of 400 secs. The stablising time is different for different combinations of concentrations and loads.

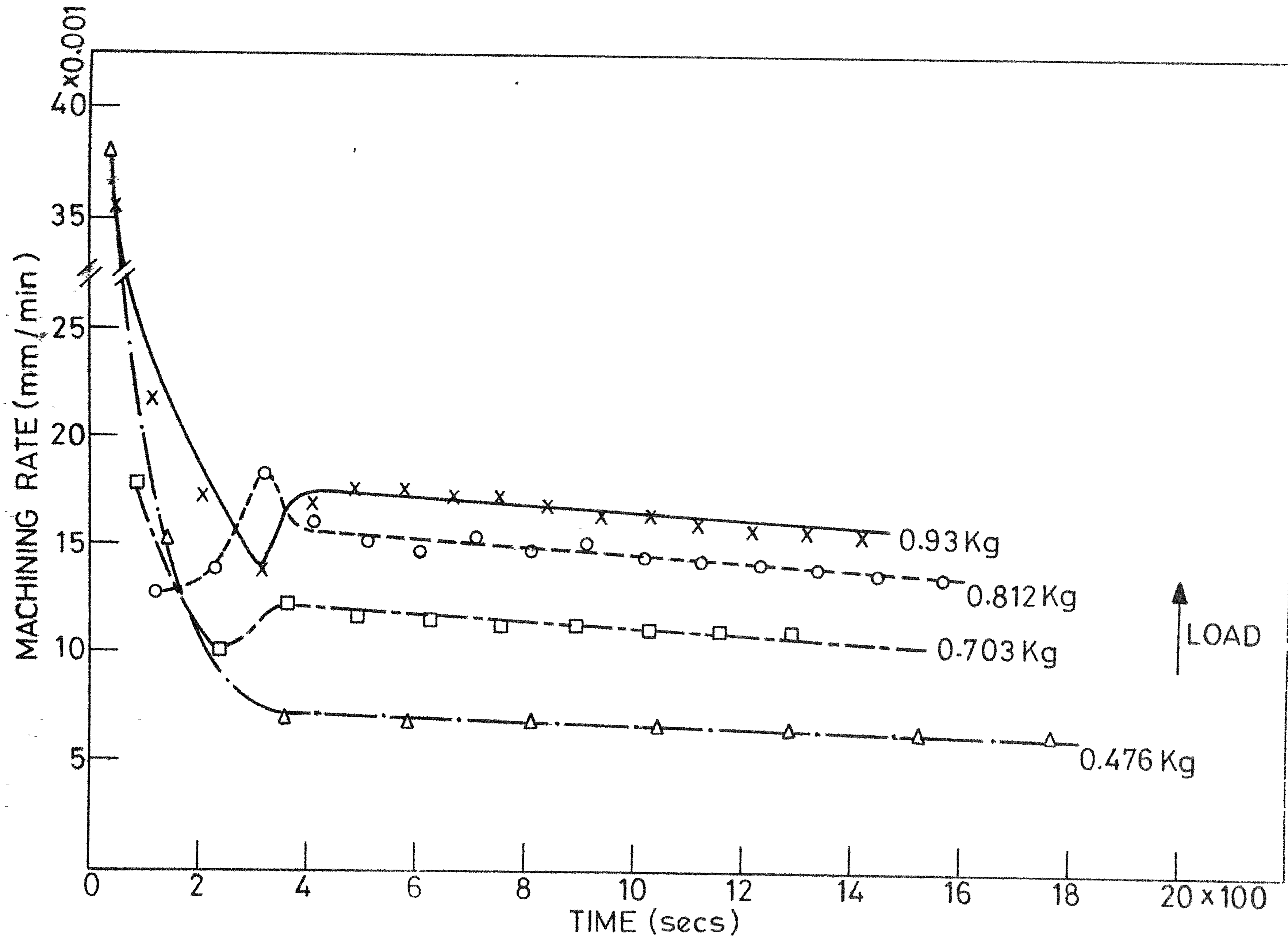
The high value of indicated machining rate in the initial stages is explained with the help of Fig. 8. Fig. 8(a) corresponds to the initial position of tool. In Fig. 8(b), due to penetration of abrasive particles in the workpiece, the tool has come down and the position indicator reads A. However, as seen from Fig. 8(b), actual depth of cut (ADC) is zero whereas virtual depth of cut (VDC) is equal to A. Fig. 8(c) shows that after some machining the tool has moved down such that the actual depth cut is X and virtual depth cut indicated



Variation of machining rate with time for various loads

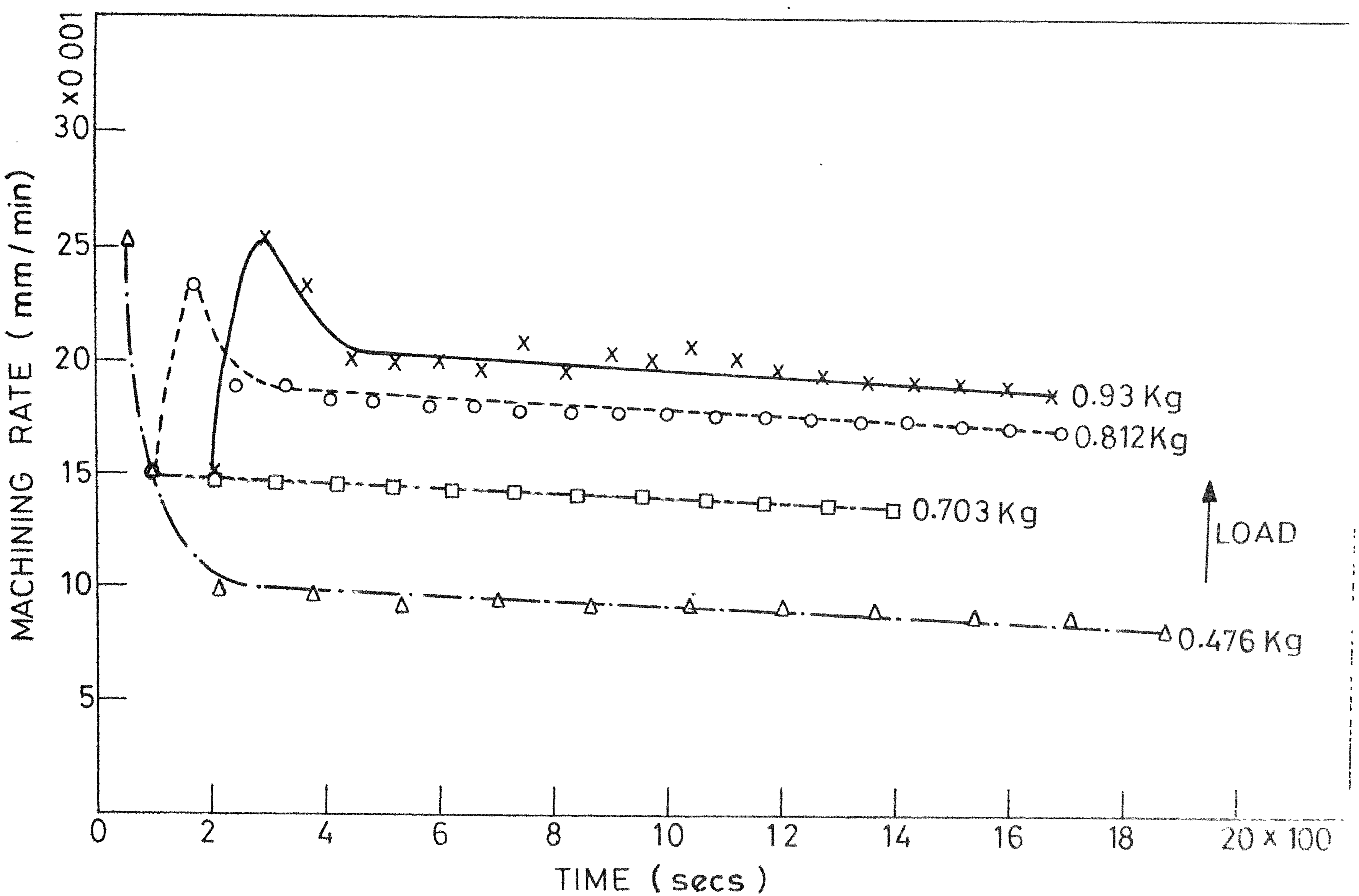
CONCENTRATION 0.125

FIG. 3



machining rate with time for various loads.

FIG.4

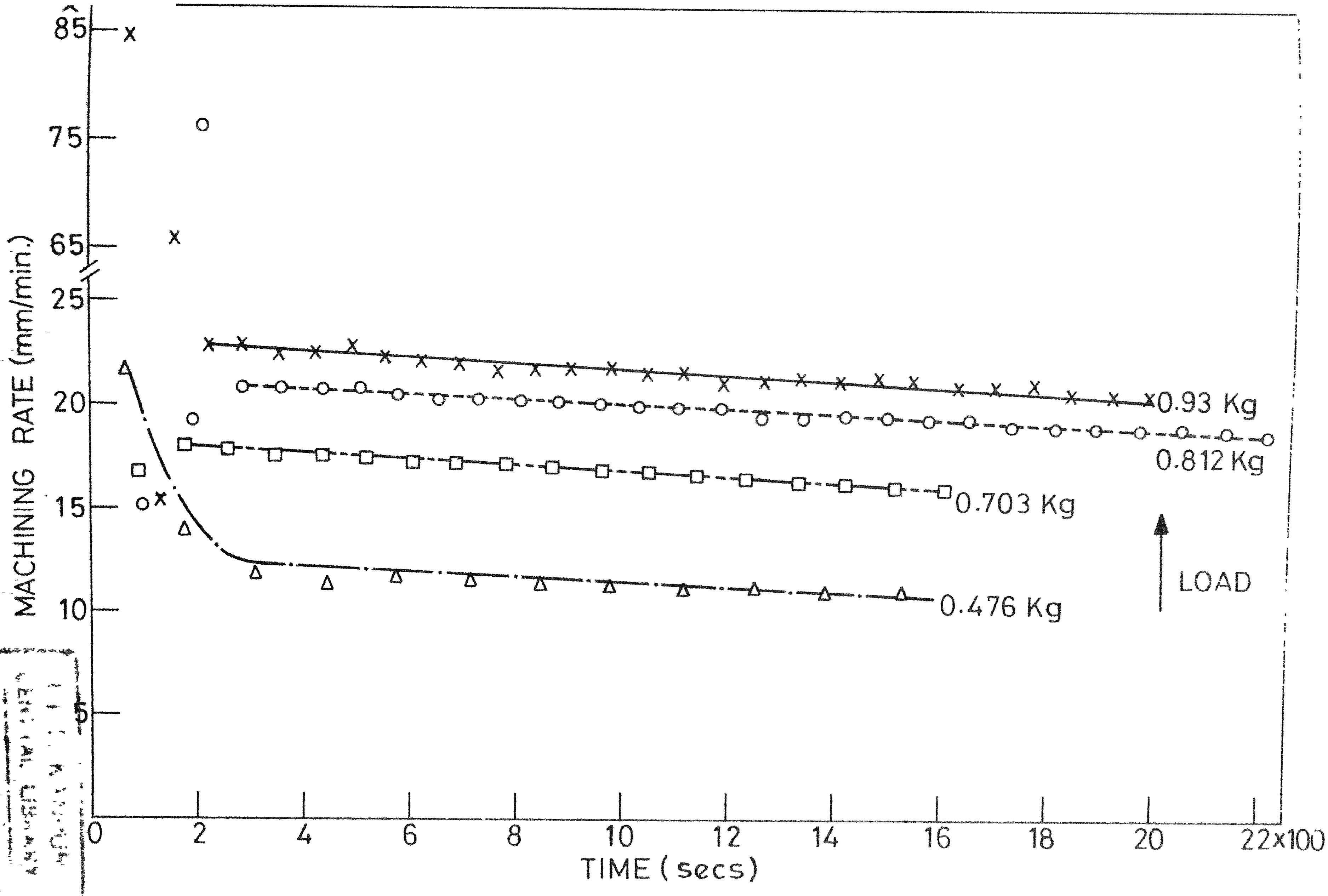


Variation of machining rate with time for various loads.

CONCENTRATION 0.167

FIG. 5

[redacted]



Variation of machining rate with time for various loads.

CONCENTRATION 0.200

FIG. 6